Auditory brainstem responses to chirps delivered by different insert earphones

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The frequency response and sensitivity of the ER-3A and ER-2 insert earphones are measured in the occluded-ear simulator using three ear canal extensions. Compared to the other two extensions, the DB 0370 (Brüel & Kjær), which is recommended by the international standards, introduces a significant resonance peak around 4500 Hz. The ER-3A has an amplitude response like a band-pass filter (1400 Hz, 6 dB/octave – 4000 Hz, −36 dB/octave), and a group delay with "ripples" of up to ±0.5 ms, while the ER-2 has an amplitude response, and a group delay which are flat and smooth up to above 10000 Hz. Both earphones are used to record auditory brainstem responses, ABRs, from 22 normal-hearing ears in response to two chirps and a click at levels from 20 to 80 dB nHL. While the click-ABRs are slightly larger for ER-2 than for ER-3A, the chirp-ABRs are much larger for ER-2 than for ER-3A at levels below 60 dB nHL. With a simulated amplitude response of the ER-3A and the smooth group delay of the ER-2 it is shown that the increased chirp-ABR amplitude with the ER-2 is caused by its broader amplitude response and not by its smoother group delay.
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I. INTRODUCTION

A. Background

A chirp (i.e., an upward chirp) refers to a brief, broadband stimulus, which attempts to compensate for the temporal delay between the excitation of different frequency regions in the auditory periphery. Chirps and clicks are used for the recording of early electrophysiological responses such as the auditory brain stem response, ABR. While there have been previous studies using chirps, the first comprehensive description and mathematical formulation of the chirp was presented by Dau *et al*. (2000), and since then several experiments with chirps have been carried out and described in the international literature. Still, the chirp is a relatively novel stimulus; and, while many of these experiments have uncovered important characteristics of the chirp, they have also clearly demonstrated that many factors affect its utility. There is now a need for more systematic studies of some of these factors such as the use of different earphones in presenting the chirp stimuli.

For the recording of chirp-evoked ABRs, auditory steady-state responses, ASSRs, and post-auricular muscle responses, PAM responses, the ER-2 earphone was used by Dau *et al*. (2000), Wegner and Dau (2002), Fobel and Dau (2004), Elberling and Don (2008), Elberling *et al*. (2010), and Petoe *et al*. (2010b). The ER-2 earphone was also used by Don *et al*. (2005) to record the derived-band ABR-latencies used to formulate the traveling wave model for the chirp designed by Elberling and Don (2008). The ER-3A earphone was used by Bell *et al*. (2002), Purdy *et al*. (2005), Elberling *et al*. (2007), Cebulla and Elberling (2010), Elberling and Don (2010), and Petoe *et al*. (2010a). Both earphones were used to study the PAM response by Agung *et al*. (2005). A few other earphones have also been applied. In order to study the ASSR to chirps and other brief stimuli the HDA-280 headphone was used by Cebulla *et al*. (2007), and to evaluate detection and perception of short chirps the AKG 240-D headphone was used by Uppenkamp *et al*. (2001). As can be seen from this brief review, most of the chirp studies related to electrophysiology have used either the ER-2 or the ER-3A earphone.

Available information, which has been put together from a variety of sources (brochures, informal laboratory tests, unpublished reports, textbook chapters, formal publications, etc.), leaves the impression that significant differences exist between the frequency responses of the two earphones (e.g., Richter and Fedtke, 2005) and between their sensitivity. Some of the differences between the frequency responses are specifically related to the reproduction of high frequency sounds and to the smoothness of the phase response or group delay function. The former would influence the effective excitation area to broadband stimulation, while the later, in

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principle, could influence the efficiency of the delay compensation offered by a chirp. Thus, both differences could have an effect on the recorded response amplitude. Therefore, before the results from different chirp experiments can be compared and discussed in details, there is a need to identify the differences between the insert earphones (i.e., ER-2 and ER-3A), which are most important and relevant for the recording of early responses from the auditory pathway.

B. Aim of the present study

In order to address the problem raised above there are three specific aims of the present study.

First, we want to describe the acoustical parameters of the ER-2 and ER-3A insert earphones that are relevant for the recording of ABRs using click and chirp stimuli. Because internationally standardized calibration values (ISO 389-6, 2007) at present exist only for the occluded-ear simulator (IEC 60318-4, 2010), only measurements in this simulator will be considered.

Second, we want to compare the ABR characteristics in response to click and chirp stimuli delivered by the ER-2 and ER-3A earphones obtained from a group of normal-hearing young adults. The characteristics will consist of the ABR amplitude, latency, waveform morphology, and peak resolution.

Third, we want to investigate the most likely causes for any identified ABR characteristics which are related to differences between the two earphones.

II. EARPHONE ACOUSTICS

A. Acoustical measurements

The amplitude and phase response of the insert earphones, ER-3A and ER-2 (10 Ω, Etymotic Research Inc.) are measured in the occluded-ear simulator, which is specified in the international standard, IEC 60318-4 (2010). In turn, two earphones (the left and right earphone of an earphone pair) are connected to the occluded-ear simulator using three different ear canal extensions as shown in Fig. 1. The two connections, which use the External Ear Simulator, DB 2012 (Brüel & Kjær), and the Ear Mould Simulator, DB 2015 (Brüel & Kjær), are acoustically very similar and they both attempt to simulate average *in situ* conditions (i.e., the sound pressure at the level of the ear drum). The physical dimensions of the earphones (tubing and ear-tip), as they are applied clinically, are maintained all the way to the reference plane of the occluded-ear simulator. The third connection, which uses the Ear Mould Simulator (or Ear-Insert Simulator), DB 0370 (Brüel & Kjær), is identical to the coupling suggested in the international standards IEC 60318-4 (2010) and ISO 389-2 (1994) to be used for the calibration of both pure tones (ISO 389-2, 1994) and transient stimuli (ISO 389-6, 2007) – see also Richter and Fedtke (2005), and Poulsen (1991). However, the dimensions of the DB 0370 deviate significantly from the dimensions of the standard ear-tips, ER1-14A (ER-2) and ER3-14A (ER-3A) which are specified for each of the two earphones. The inner diameters are 1.37 mm and 1.93 mm for the ER-2 ear-tip (ER1-14A) and the ER-3A ear-tip (ER3-14A), respectively. However, the bore diameter

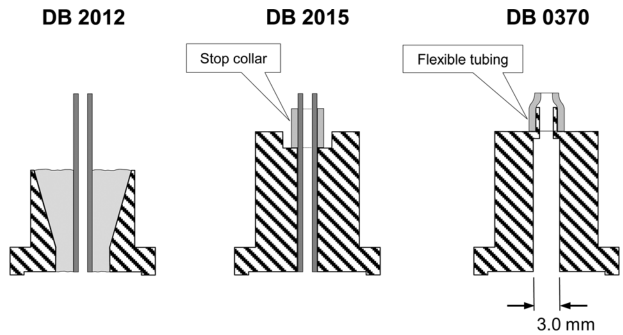

FIG. 1. The figure shows the three different ear canal extensions, DB 2012, DB 2015, and DB 0370 (Brüel & Kjær), used to connect the insert earphones to the occluded-ear simulator (IEC 60318-4, 2010). With the External Ear Simulator, DB 2012, the ear tip is placed with its end flush with the lower flange of the conical ear canal extension. With the Ear Mould Simulator, DB 2015, the tubing of the ear tip (with the yellow foam removed) is inserted into the ear canal extension using a short piece of tubing as a stop collar. For practical reasons this connection is preferred over the DB 2012. With the Ear Mould Simulator (or Ear-Insert Simulator), DB 0370, the long tubing of the insert earphone is attached to the top of the ear canal extension using the nipple and a short piece of flexible tubing.

of the DB 0370 is 3.0 mm (and the length 18.0 mm) and therefore, provides a step-up of the tubing's cross sectional area (a horn effect) and a theoretical quarter-wave-length resonance at about 4800 Hz (based on simplified assumptions). Because the diameter difference from the bore in the DB 0370 is greater for the ER1-14A (ER-2), the effect of DB 0370 on the earphone response is expected to be larger for the ER-2 than for the ER-3A.

Measurements of the amplitude and phase responses are carried out by means of a Brüel & Kjær PULSE system (PULSE LabShop v. 15.1.0.15), and are based on FFT computations and spectral averaging in a 6400 points frequency buffer. The frequency range is from 0 to 12 800 Hz and the frequency resolution 2 Hz. The responses for each of the two earphones (left and right) are very similar for each connection (ear canal extension), and the frequency responses for the left and right earphone are therefore averaged. As expected, the two connections DB 2012 and DB 2015 give very similar responses[1] and the mean responses are therefore computed and referred to as connection DB 2012/15. The amplitude and phase responses for the two earphones measured with the connection DB 0370 are subsequently used to calculate simulated earphone responses to a standard 100 μs click stimulus. Complex multiplications in the spectral domain followed by inverse FFT are used for these calculations.

Compared to ER-3A, the ER-2 earphone has a much lower sensitivity and a limited maximum output level, which for the 100 μs click is estimated to be 100–115 dB peak SPL in the Zwislocki coupler (Etymotic Research, 2002). The standardized RETSPL-value for a click by the ER-2 corresponds to 43.5 dB p.-p.e.SPL[2] (ISO 389-6, 2007), which means that at a psycho-physical level of 60 dB nHL, the sound pressure level will be 103.5 dB p.-p.e.SPL in the occluded-ear simulator with the DB 0370 connection. In order to evaluate the maximum click output level without distortion of the ER-2 earphone, the output spectrum of a band-limited (350–10 000 Hz) 100 μs click is monitored on a spectrum analyzer (Stanford Research System, SR770). The click distortion is evaluated by the level of the distortion products that are generated above 10 000 Hz. The maximum allowable distortion is thus set to a level where the distortion products are 30 dB below the signal level at 1000 Hz (distortion approx. 3%).

B. Results

The sensitivity responses are shown in Fig. 2. With the DB 2012/15 connection, the sensitivity at 1000 Hz for the ER-3A is measured to 34.5 dB re 1 Pa/V (∼128.5 dB SPL/V) and for the ER-2 to 6.0 dB re 1 Pa/V (∼100.0 dB SPL/V). This corresponds to a sensitivity difference of 28.5 dB. With the DB 0370 connection, both amplitude responses have a clear resonance peak at frequencies around 4500 Hz, which is close to the theoretical resonance frequency at 4800 Hz. At this frequency, the difference between the earphone sensitivity obtained with the DB 0370 and the sensitivity obtained with the DB 2012/15 is about 6.5 dB for the ER-3A and about 11.5 dB for the ER-2 earphone. As predicted, the effect of DB 0370 on earphone sensitivity is greater for ER-2 than for ER-3A.

For the simulations of the click waveform, the amplitude responses of the two earphones with the DB 0370 connection are normalized to zero dB at 1000 Hz, and then the two simulated click responses are computed. In the international standard (ISO 389-6, 2007) the reference calibration values (RETSPL-values) for the 100 μs click are given to 35.5 dB p.-p.e.SPL (ER-3A) and 43.5 dB p.-p.e.SPL (ER-2)[3]—i.e., a difference of 8.0 dB. In order to obtain the same difference between the peak-peak values of the simulated click waveforms the amplitude response of ER-2 has to be increased by 3.5 dB. The corresponding amplitude responses of the two earphones, but with the DB 2012/15 connection, are displayed in Fig. 3(A). This figure shows the spectral amplitude relationship of the earphones when the same simulated click-level in dB nHL is obtained from the two earphones. In this condition, the two earphones provide the same amount of acoustic energy in the frequency range 1500–3500 Hz. The amplitude response of the ER-2 is flat, and, compared to the ER-3A earphone, gives relatively much higher output in the frequency range above 4000–5000 Hz (30–35 dB higher around 8000 Hz).

The phase responses are dominated by a large acoustical delay, which mainly is caused by the long earphone tubing (ER-3A: 256 mm, and ER-2: 270 mm) plus the length of the standard ear tips (22 mm). The phase responses are therefore compensated for a 1 ms delay[4] before they are plotted in Fig. 3(B) (for the DB 2012/15 connection).

Corresponding to the un-compensated phase responses, the group delay functions[5] are calculated and plotted in Fig. 4. In the frequency range 500–10 000 Hz, both functions show an average group delay of approximately 1 ms, but whereas the group delay function for the ER-2 is relatively flat, the group delay function for the ER-3A is "rippled," and fluctuates up to almost ±0.5 ms.

To evaluate the output level of the ER-2 earphone that maximally can be used without distortion the output spectra of eight individual ER-2 earphones are measured in the occluded-ear simulator (with the DB 0370) for varying levels of a band-limited 100 μs click. With the definition given above, a mean maximum click level without distortion is found to 68.5 dB nHL (SD = 0.3 dB) across the sample of eight ER-2 earphones.

C. Discussion

When connecting the insert earphones to the occluded-ear simulator with the DB 0370 an increased sensitivity is

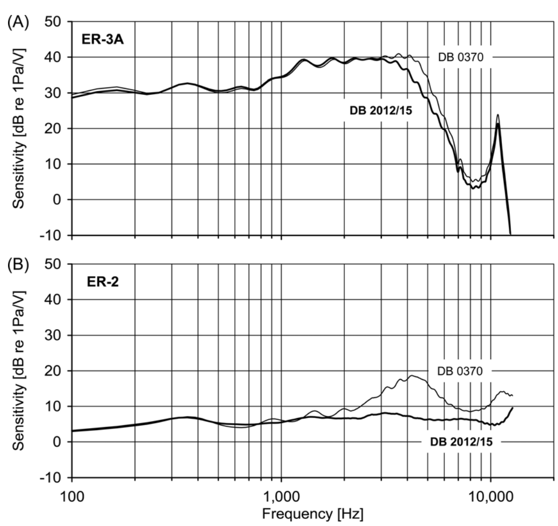

FIG. 2. Sensitivity responses of the (a) ER-3A and (b) ER-2 measured in the occluded-ear simulator (IEC 60318-4, 2010). The sensitivity is given in dB re 1 Pa/V (1 Pa/V ∼ 94.0 dB SPL/V). Sensitivity functions are shown for the DB 2012/15 ear canal extension (thick line) as well as for the DB 0370 (thin line).

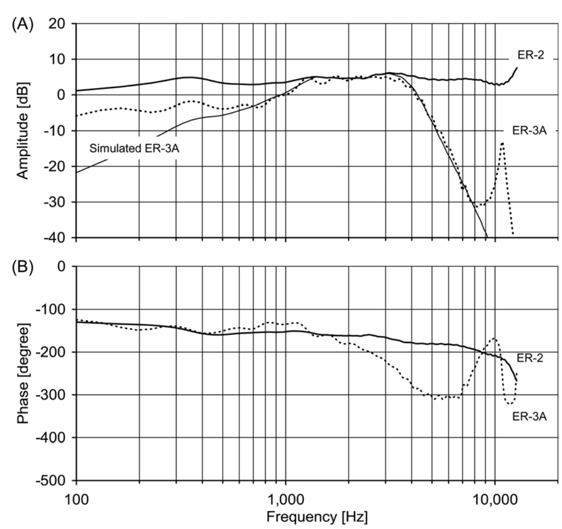

FIG. 3. Frequency responses for the ER-2 (full line) and ER-3A (dotted line) in the occluded-ear simulator measured with the DB 2012/15 ear canal extension. (a) The amplitude responses are shown using an arbitrary amplitude dB-scale. The level at 1000 Hz is 0 dB for the ER-3A and 3.5 dB for the ER-2. In this relative condition the simulated click responses (with the DB 0370 extension) deviate by 8.0 dB p.-p.e.SPL (see text for details). The "Simulated ER-3A" (thin line) shows the combined amplitude response of a band-pass filter and the ER-2 earphone. This filter is used to simulate the amplitude response of the ER-3A (see Sec. IV). (b) The phase responses are shown using a [degree]-scale. Since the absolute phase is dominated by a large delay in the earphones' long tubing, the phase responses shown here are compensated for a 1 ms delay.

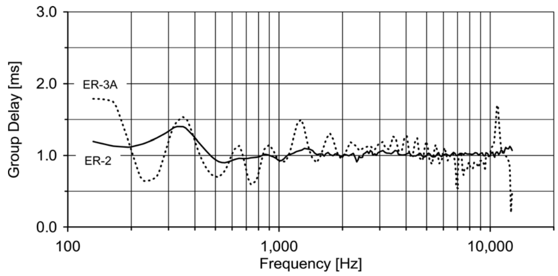

FIG. 4. Group delay functions for the ER-2 (full line) and ER-3A (dotted line) are calculated from the original phase responses, and shown using a [ms]-scale. Both earphones show an average group delay of approximately 1 ms in the frequency range 500–10 000 Hz. However, whereas the group delay function of the ER-2 is relatively flat, the group delay function of the ER-3A is rippled with fluctuations of up to ±0.5 ms.

measured around 4500 Hz due to the quarter-wave-length resonance created by the DB 0370. Therefore, amplitude responses obtained with this connection do not reflect the real *in situ* frequency responses of the earphones. At around 4500 Hz the sensitivity is about 6.5 dB too high for the ER-3A and about 11.5 dB too high for the ER-2 earphone. For acoustical measurements of the insert earphones in the occluded-ear simulator a connection using the DB 2012/15 ear canal extension (Fig. 3) should therefore be preferred. In Fig. 3(A), the amplitude responses are adjusted to show the condition when the two earphones present a 100 μs click to the ear with the same estimated level in dB nHL. The 0 dB reference on the y-axis corresponds at 1000 Hz to a sensitivity of 128.5 dB SPL/V for the ER-3A and to 96.5 dB SPL/V (100.0 dB − 3.5 dB) for the ER-2, which means that in this condition the sensitivity difference between the two earphones is 32 dB.

Because the two earphones have quite different sensitivities and amplitude responses the calibration of click and chirp stimuli is challenging. As described above, RETSPL-values for the 100 μs click exist for both earphones and are standardized in ISO 389-6 (2007). For the CE-Chirp a reference value for the ER-3A has been established by *Physikalisch-Technische Bundesanstalt* (PTB) (Braunschweig, Germany) in accordance with the recommendations described in ISO 389-9 (2009). However, for the ER-2 earphone, and for chirps with amplitude-spectra that differ from the amplitude spectrum of the 100 μs click, no reference values exist. Provided that the electrical amplitude spectrum of a broadband stimulus is reasonably flat and smooth the 32 dB sensitivity difference described above may be used to approximate the correct calibration value. If, for instance, the ABR-equipment is calibrated with the ER-3A earphone, then the electrical output applied to the ER-2 should be increased by 32 dB in order to obtain the same stimulus level in dB nHL as with the ER-3A. However, the 32 dB sensitivity difference is only valid for the 10 Ω-versions of the earphones evaluated here. Earphones with other nominal impedance values (e.g., 50 and 300 Ω) have different sensitivities, but, as far as we have experienced and measured, the shape of the amplitude response remains almost unchanged. The calibration principle sketched above has been adopted for the comparative ABR-studies described in the next sections of the present communication.

Additionally to the phase responses, the corresponding group delay functions are also calculated. Chirp stimuli are designed using an appropriate delay model (for instance the traveling delay in the cochlea), which is regarded as being the group delay function of the system it characterizes (Dau *et al.*, 2000; Elberling *et al.*, 2007). The earphones' group delay functions may therefore be more relevant than their phase responses, when evaluating the temporal influence on the chirp stimuli caused by the different earphones.

III. EARPHONE DIFFERENCES

A. Method

1. Subjects

The group of test subjects consists of eleven young adults (six females and five males) with ages ranging from 20 to 26 years. In the frequency range from 125 Hz to 8000 Hz all subjects have pure-tone thresholds equal to or better than 10 dB HL. Both ears are tested on all test subjects (N = 22 ears).

During the recruitment process the test procedure is explained to the participating subjects and all questions answered concerning the participation and the purpose of the experimental study. Finally a standard consent form is read and signed. In accordance with the general rules of the Danish Central Ethical Committee and the Danish Medicines Agency, a written study approval is not required when the testing is part of a quality control procedure with CE-marked equipment (used as intended).

2. Stimuli

Three short stimuli are used to generate individual ABR responses using two insert earphones ER-3A and ER-2. The three stimuli are the following: (1) a standard 100 μs click stimulus (limited to the frequency range 350–10 000 Hz; referred to as the Click), (2) a level-independent chirp, CE-Chirp (350–11 300 Hz), and (3) a level-specific chirp, LS-Chirp (350–11 300 Hz), which briefly is explained in the following. The direct approach described by Elberling and Don (2010) uses the latencies of ABRs to octave-band chirp stimuli (subcomponents of the broadband CE-Chirp) to find the necessary delay compensation. The temporal shifts which, for each level, align the corresponding octave-band ABRs, lead to the mathematical formulation of the level-dependent delay compensation for the LS-Chirp. Thus, for each level, the LS-Chirp ensures that all the octave-band chirps, within the broadband chirp, produce ABRs with the same latency. See Elberling and Don (2010) for further details.

With the ER-3A earphone the stimuli are tested at four levels (20, 40, 60, and 80 dB nHL). However, with the ER-2 earphone the stimuli are tested only at the three lower levels (20, 40, and 60 dB nHL), due to restrictions of the maximum output level for this earphone (see previous Sec. II B). The stimulus waveforms of the Click and the CE-Chirp are level independent, whereas the stimulus waveform of the LS-Chirp changes with level. The LS-Chirp uses a modified version of the underlying delay model which takes into account the change in cochlear delay with level and upward spread of excitation at levels above approximately 60 dB nHL (Elberling and Don, 2010). The electrical waveforms of all the chirps have the same amplitude spectrum, which is flat within five octaves (350 – 11 300 Hz; approx. −3 dB points). Relative to the Click, the chirp waveforms are delayed by 1.5 ms (10.000 Hz component) in order to align the latency of the chirp ABR to the latency of the Click ABR, at lower levels in normal-hearing subjects. The electrical waveforms of the five stimuli and their timing are shown in Fig. 5. For all stimuli, the data collection is delayed by 1 ms in order to compensate for the acoustical delay in the earphones which mainly is due to the long sound tubing (see previous Sec. II B).

Two sets of earphones are used: ER-3A and ER-2. The ER-3A (Ear-Tone ABR version) has a nominal electrical impedance of 50 Ω, whereas the ER-2 (Etymotic Research version) has a nominal electrical impedance of 10 Ω. We have measured an average sensitivity difference of 6.5 dB (500–4000 Hz) between 10 Ω and 50 Ω versions of the ER-3A (the 50 Ω version being less sensitive). In the previous section, a sensitivity difference of 32 dB was found between the ER-3A and ER-2 earphones (both 10 Ω) for the calibration of a standard click stimulus. For the two earphones used here (ER-3A, 50 Ω and ER-2, 10 Ω) the corresponding sensitivity difference is therefore, 32 – 6.5 = 25.5 ∼ 25 dB.

For the ER-3A earphone, the Click and the CE-Chirp are calibrated in the occluded-ear simulator (IEC 60318-4, 2010). For the Click, the standardized RETSPL-value of 35.5 dB p.-p.e.SPL is used (ISO 389-6, 2007). For the CE-Chirp, a RETSPL-value of 32.0 dB p.-p.e.SPL is used; this value is provided by PTB (Physikalisch-Technische Bundesanstalt, Braunschweig, Germany) and based on psycho-acoustic experiments in accordance with standardized recommendations (ISO 389-9, 2009). The LS-Chirp is calibrated via the

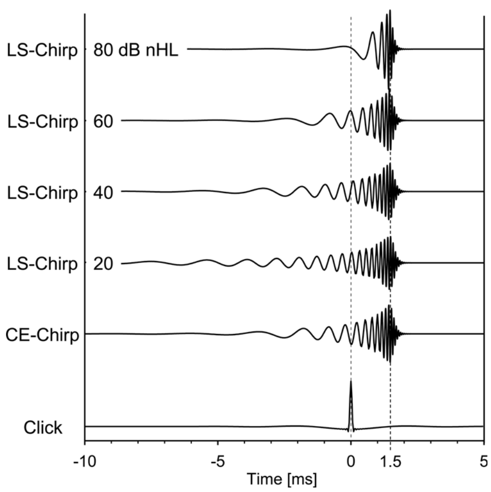

FIG. 5. The figure shows the electrical waveforms of the LS-Chirp, the CE-Chirp and the Click. The 0 ms point on the time axis indicates the estimated arrival time of the Click at the tympanic membrane. The 10 000 Hz-component of the chirps is delayed 1.5 ms in order to align the ABR latencies to the chirps with the latencies to the Click at lower levels in normal-hearing subjects. The five chirps have identical amplitude spectra (spectrum levels), and the waveforms are scaled up by a factor of two compared to the Click.

CE-Chirp due to the fact that the two stimuli have identical spectrum levels (Elberling *et al.*, 2007, p. 2783; Uppenkamp *et al.*, 2001, p. 75). For the ER-2 earphone, calibration is obtained by changing the electrical output to the earphone by +25 dB (see Sec. II).

The stimuli are presented with alternating polarity and at a stimulus rate of 27.1/s. The standardized calibration values, which correspond to the behavioral thresholds in normal-hearing individuals at a stimulus rate of 20/s, are used regardless of the rate that actually is applied (Lightfoot *et al.*, 2007).

3. ABR recording

The recording procedure is the same as used previously (Elberling and Don, 2010; Elberling *et al.*, 2010) but is briefly summarized in the following. The recordings are obtained with the Eclipse EP25 ABR system® by Interacoustics. The test subjects are placed on a couch in an ordinary, silent test room. The electrical activity is picked-up between two electrodes; one placed as high as possible on the mid-frontal area (F_z), and the other placed on the ipsi-lateral mastoid (M_1 or M_2), while an additional electrode is placed on the cheek and used as ground. All three electrodes are disposables. The electrical activity is band-pass filtered from 100 Hz (12 dB/octave) to 3000 Hz (-12 dB/octave). In the ABR system a running estimate of the physiological background noise is calculated (Elberling and Don, 1984) and weighted averaging is used (Elberling and Wahlgreen, 1985), in order to minimize the destructive effect of spurious changes in the level of the physiological background noise. A residual background noise level of 30 nV_{rms} is used as stop criterion (Don and Elberling, 1994), which on the average is obtained after approximately 5000 sweeps.

4. Analysis

The most prominent response peak, within the first 10 ms window, is identified in each recording and referred to as wave V. Two parameters of the identified peak, latency and amplitude (from the peak of wave V to the following trough), are automatically measured. By means of the Kolmogorov-Smirnov test (Siegel, 1956) the dataset for each parameter and each condition (stimulus type, level, and earphone = 21 conditions) is checked for normality, in order to assure that none of the datasets deviate significantly from a Gaussian distribution. Datasets are compared statistically across conditions by means of the Wilcoxon mached pair signed-rank test (Siegel, 1956). Counter measures for repeated testing is introduced by Bonferroni's correction (Hochberg and Tamhane, 1987).

The morphology of the ABRs in the different conditions is evaluated from the Grand Average ABR waveforms. For each condition the Grand Average is calculated in the following way: each of the 22 recordings is temporally shifted so the wave V latency coincides with the mean latency in the actual condition (see Tables I and II). The Grand Average is computed as the average of the 22 temporally shifted waveforms. By using the mean latency of wave V as the temporal reference, the Grand Average will reproduce the true average

TABLE I. The table shows group data for the ER-3A earphone (mean and standard deviation; N = 22 ears). ABR amplitude [nV] (top) and ABR latency [ms] (bottom) for the three stimuli at four levels.

Level	Click		CE-Chirp		LS-Chirp	
dB nHL	Mean	SD	Mean	SD	Mean	SD
			Amplitude p-p (nV)			
80	615	143	450	160	682	203
60	389	91	525	191	561	143
40	309	78	495	141	503	115
20	180	55	276	89	254	90
			Latency (ms)			
80	5.38	0.26	4.58	0.67	6.37	0.33
60	5.89	0.34	5.53	0.37	6.05	0.47
40	6.63	0.38	6.88	0.46	6.81	0.41
20	7.73	0.48	8.11	0.48	7.60	0.43

ABR morphology at wave V and in its vicinity, whereas the average waveform further away from wave V will be smeared. In order to reduce the impact of the post-auricular muscle response (PAM), which is dominating the overall recording amplitude in 56 of the 462 ABR recordings (∼12%), the 9–15 ms PAM response window is down-scaled by the inverse of the rms-amplitude before the Grand Averages are calculated.

B. Results

None of the datasets (amplitude and latency) describing each condition (earphone, stimulus, and level) deviate significantly from a Gaussian distribution, even at a 20% level of significance. The mean and standard deviation of the ABR wave V (amplitude and latency) are therefore calculated and shown in Table I (ER-3A) and Table II (ER-2). The corresponding data are plotted graphically in Fig. 6.

For both earphones, the two chirps generate significantly ($p < 0.001$) larger ABRs than the Click at 20, 40, and 60 dB nHL. The data for the ER-2 earphone deviate, in some of the conditions, significantly from the corresponding ER-3A data

TABLE II. The table shows group data for the ER-2 earphone (mean and standard deviation; N = 22 ears). ABR amplitude [nV] (top) and ABR latency [ms] (bottom) for the three stimuli at three levels.

Level	Click		CE-Chirp		LS-Chirp	
dB nHL	Mean	SD	Mean	SD	Mean	SD
			Amplitude p-p (nV)			
80	-	-	-	-	-	-
60	442	111	558	152	584	134
40	336	99	610	158	614	149
20	216	70	386	110	419	145
			Latency (ms)			
80	-	-	-	-	-	-
60	5.61	0.32	4.90	0.38	5.97	0.43
40	6.33	0.41	6.82	0.36	6.77	0.39
20	7.08	0.35	7.84	0.36	7.64	0.37

(see Fig. 6). For the Click, there are significant differences both in amplitude ($p < 0.01$) and latency ($p < 0.001$) at 20, 40 (only latency) and 60 dB nHL; for the CE-Chirp, there are significant differences in both amplitude and latency ($p < 0.001$) at 20, 40 (only amplitude) and 60 dB nHL (only latency); and for the LS-Chirp, there are significant differences in amplitude ($p < 0.001$) at 20 and 40 dB nHL.

The Grand Average ABR-waveforms are displayed in Fig. 7 for each condition (earphone, stimulus, and level). These Grand Average waveforms reproduce the classical ABR-morphology well except for two conditions of the CE-Chirp, (1) at 60 dB nHL for the ER-2, and (2) at 80 dB nHL for the ER-3A.

Differences in the obtained waveform resolution between the earphones are evaluated qualitatively by counting the number of recordings in which each of the three main ABR wave peaks (I, III, and V) can be identified visually for each condition (earphone, stimulus, and level). The results are shown in the histograms in Fig. 8. Wave V is resolved equally well by the two earphones for all three stimuli. Wave III is resolved equally well by the two earphones for the Click. For the two chirps, however, the ER-2 resolves wave III much more frequently than the ER-3A. Wave I is resolved much more frequently by the ER-2 than by the ER-3A, and for the LS-Chirp the ER-2 is able to resolve wave I in all recordings at all three levels.

C. Discussion

The most striking difference between the two earphones is the significantly higher response amplitude at 20 and 40 dB nHL obtained for the two chirps by the ER-2 compared to the ER-3A. It should be noted, that at 60 dB nHL no significant difference is found between the ABR amplitudes obtained by the two earphones. This seems to indicate that the ER-2 earphone is a better choice when using chirp stimuli for broadband ABR recordings in normal hearing adults at lower stimulus levels (less than 60 dB nHL).

With the ER-3A, the observed, mean ABR-amplitude increases for both chirps ($p < 0.01$ – for the LS-Chirp) when the level increases from 40 to 60 dB nHL. However with the ER-2, the observed, mean ABR-amplitude decreases (NS) for both chirps when the level increases from 40 to 60 dB nHL. This observation is in agreement with the findings by Fobel and Dau (2004, M- and O-chirp), Elberling and Don (2008, CE-Chirp), and Elberling *et al.* (2010, Chirp-3), which all observed a drop in the chirp-ABR amplitude when the level changed from 40 (or 50) to 60 dB nHL using the ER-2 earphone.

The drop in amplitude with the ER-2 has previously been related to upward spread of excitation (Elberling and Don, 2008; Elberling *et al.*, 2010), and the corresponding drop in amplitude for the CE-Chirp with the ER-3A, when the level changes from 60 to 80 dB nHL, may also be caused by the same non-linear process. For both earphones it appears that the levels of the CE-Chirp where the ABR has dropped in amplitude, i.e., about 60 dB nHL for the ER-2 and 80 dB nHL for the ER-3A, also are associated with a poorly resolved ABR waveform (see Fig. 7).

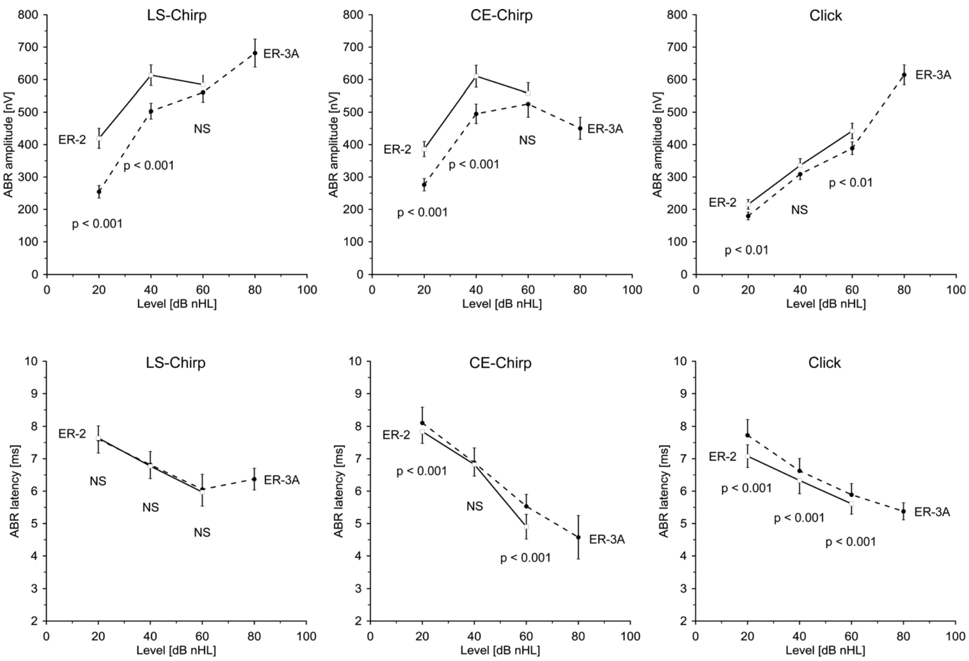

FIG. 6. ABR amplitude [nV] (top) and ABR latency [ms] (bottom) are shown for each of the three stimuli ((left) LS-Chirp, (middle) CE-Chirp, and (right) Click), and for each stimulus level [dB nHL]. The values are taken from Table I (ER-3A) and Table II (ER-2), and the mean values are shown for the ER-3A (closed symbols, broken line) and for the ER-2 (open symbols, full line). The amplitude variance is indicated by ± 1 Standard Error, SE ($= \mathrm{SD}/\sqrt{N}$; $N = 22$), and the latency variance is indicated by ± 1 Standard Deviation, SD. The results of the comparative statistical testing of the response parameters from the two earphones are indicated at each level.

Based on the above arguments there appears to be two main differences between the two earphones related to the present experiment, (1) the difference in chirp-ABR amplitude at lower levels, and (2) the difference in the level at which the ABR drops in amplitude in response to the CE-Chirp. It has been found that the two earphones differ both in the amplitude-frequency response and in the group delay function. When the two earphones are calibrated to produce the same dB nHL of the Click (and the two chirps) they deliver the same amount of acoustic energy in the frequency range from 1500 to 3500 Hz. At higher frequencies the ER-2 delivers significantly more energy than the ER-3A corresponding to about 30–35 dB at 8000 Hz. For the Click-ABR the slightly increased amplitude and shorter latency obtained with the ER-2 is expected on the grounds of a broader excitation area and a higher contribution from the high-frequency region in the cochlea. For the chirp-ABR the increased amplitude obtained with the ER-2 is also expected on the grounds of a broader, synchronized excitation area. For the two earphones the ratio between upward spread of excitation and the level of direct high-frequency excitation is very different and may be the reason for the drop in ABR amplitude which is observed at different levels for the two earphones.

The sensitivity or pure tone threshold of a normal-hearing ear, using the sound pressure level at the ear drum as the reference, is reasonably flat for frequencies above 1000 Hz as indicated by the Minimum Audible Pressure (MAP) described by Killion (1978). Another MAP-estimate[6] based on pure-tone calibration values for the ER-2 and ER-3A earphones appears to follow this description but indicates also that the sensitivity falls off slightly above 4000 Hz. This implies that the contribution from the high-frequency region probably falls off when applying flat spectra stimuli. When using the ER-3A earphone, the contribution is further reduced due to its poorer high-frequency response. Because of the flatter and better high-frequency response of the ER-2, more activation occurs in these high-frequency regions at lower levels and contributes significantly to the neural response. This also suggests why the upward spread of excitation occurs at a lower level for the ER-2 than for the ER-3A earphone. It would be interesting to study these effects quantitatively in a cochlear model similar to the studies by, e.g., Dau (2003) and Junius and Dau (2005).

The results show in general that the ABR wave I and III are resolved better by the ER-2 than by the ER-3A. This finding is quite consistent with the early analysis of derived-band neural responses. Analysis of derived-band auditory compound action potentials, CAPs, (e.g., Eggermont, 1979), demonstrates that wave N_1 mainly is formed by neural activity from the cochlear high-frequency region, at higher stimulus levels. A similar analysis of derived-band ABRs (Don and Eggermont, 1978) suggests that the amplitudes of waves I and III are highly dependent on the contributions from the higher frequencies.

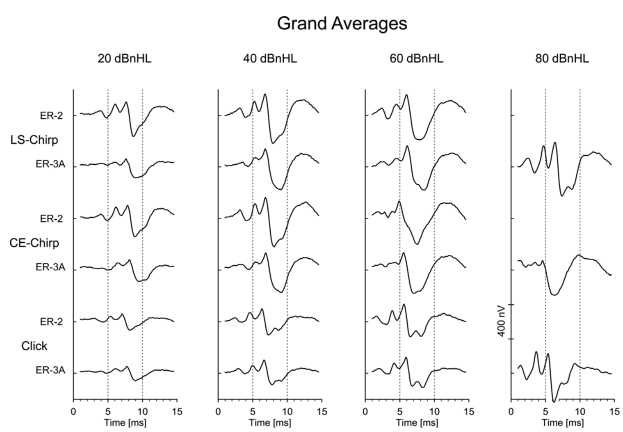

FIG. 7. Grand Average ABR waveforms from $N = 22$ ears, as a function of stimulus level, stimulus type and earphone. The Grand Averages are obtained by time-shifting the underlying individual waveforms according to wave-V latency, as described in the text.

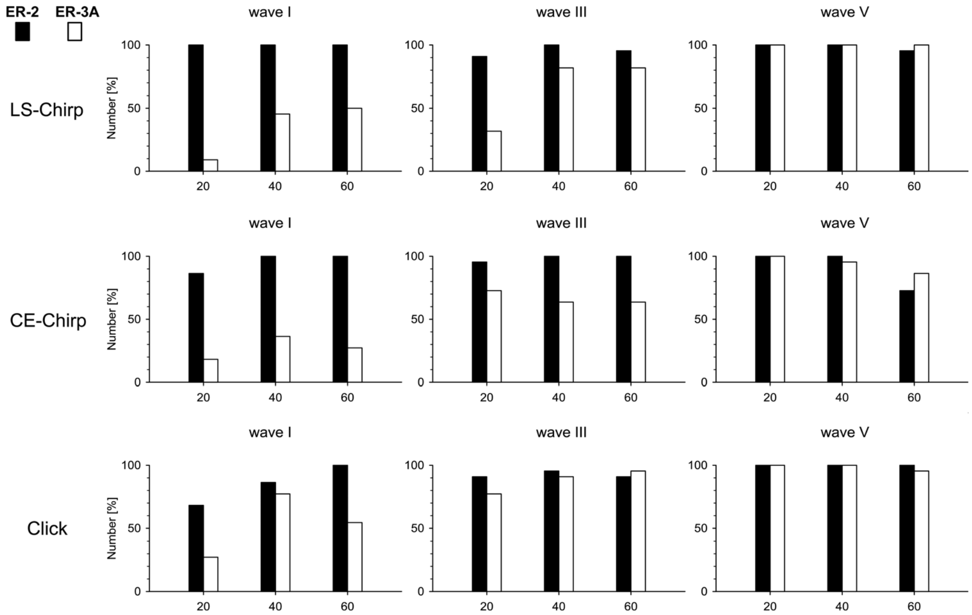

FIG. 8. Resolved response peaks corresponding to wave I, III and V, as a function of stimulus level, stimulus type, and earphone. The histograms show the number [in %] of identified wave peaks in each condition and with the results from the ER-2 (closed, black) and the ER-3A (open, white).

The rippled group delay function of the ER-3A could render the chirps less effective with this earphone compared to the ER-2. Consequently, it is not known whether it is the difference in the amplitude response or in the phase response (group delay) which is the main reason for the observed ABR differences between the two earphones. Therefore, a supplementary experiment is carried out using the ER-2 earphone with which the amplitude response of the ER-3A is simulated but preserving the smooth group delay function of the ER-2.

IV. EARPHONE SIMULATION

A. Method

The experimental method is similar to the method described above in Sec. III A, with very few exceptions. First, the group of test subjects consists of five test subjects (three females and two males) chosen among the participants in the previous experiment (Sec. III A 1). Both ears are tested on all test subjects (N = 10 ears). Next, only the LS-Chirp is used and presented at three levels (20, 40, and 60 dB nHL) using the ER-2, either with the original frequency response of the stimulus or shaped by a band-pass filter in order to simulate the amplitude response of the ER-3A earphone [shown by the thin line in Fig. 3(A)]. The amplitude response of the band-pass filter has a lower cut-off frequency of 1400 Hz (6 dB/octave) and a higher cut-off frequency of 4000 Hz (-36 dB/octave). The phase response of the filter is zero. Thus, by using this filter, the LS-Chirp will be presented with an approximate amplitude response as if it was delivered from the ER-3A earphone but with a phase response as if it was delivered from the ER-2 earphone.

B. Results

The dataset (amplitude and latency) for the two conditions (LS-Chirp and LS-Chirp in simulated ER-3A presented by the ER-2) appear not to deviate from Gaussian distributions ($p > 20\%$), and the mean and standard deviation of the ABR wave V amplitude and latency are therefore calculated and shown in Table III together with the corresponding data for the ER-3A extracted for the N = 10 ears, from the data obtained previously (Sec. III B). The amplitude data are plotted graphically in Fig. 9.

For the ten ears the ABR amplitude-functions for the LS-Chirp with the ER-2 and ER-3A are very similar to the corresponding amplitude-functions obtained in the previous experiment (N = 22, Sec. III B, Fig. 6). When the level increases from 40 to 60 dB nHL, the amplitude decreases for the ER-2, whereas it increases for the ER-3A. When the LS-Chirp is delivered by the ER-2 but with a simulated ER-3A amplitude response (Simulated ER-3A) the amplitude-function resembles the amplitude-function for the real ER-3A. This is further evaluated by the Grand Average waveforms

TABLE III. The table shows group data for the ER-2 and ER-3A earphone (mean and standard deviation; N = 10 ears). ABR amplitude [nV] (top) and ABR latency [ms] (bottom) for the the LS-Chirp at three levels with the ER-2, and four levels with the ER-3A.

	ER-2				ER-3A	
Level	LS-Chirp		LS-Chirp in simulated ER-3A		LS-Chirp	
dB nHL	Mean	SD	Mean	SD	Mean	SD
			Amplitude p-p (nV)			
80	-	-	-	-	769	210
60	637	151	564	130	595	162
40	690	146	492	102	540	94
20	454	145	255	86	258	109
			Latency (ms)			
80	-	-	-	-	6.14	0.21
60	5.85	0.28	5.68	0.23	5.85	0.33
40	6.62	0.28	6.63	0.42	6.72	0.37
20	7.40	0.29	7.46	0.43	7.48	0.39

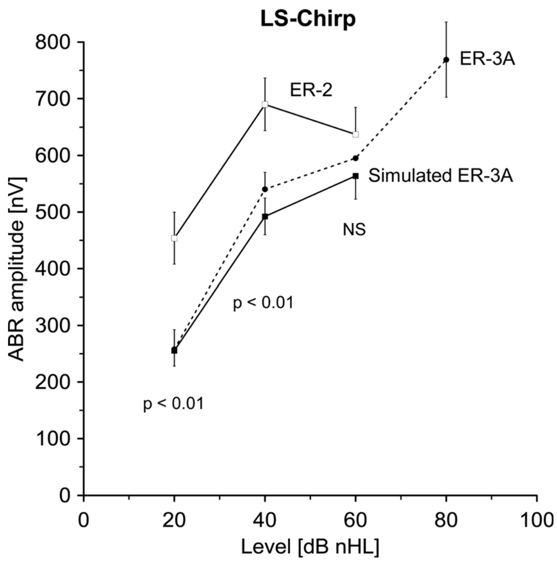

FIG. 9. ABR amplitude [nV] are shown for the LS-Chirp, delivered by the ER-2 earphone as a function of stimulus level [dB nHL]. The values are from the earphone simulation experiment and are taken from Table III. The mean values (N = 10) are shown for the ER-2 (open symbols, full line), for the "Simulated ER-3A" by the ER-2 (closed symbols, full line), and for the ER-3A (closed symbols, broken line—the data are extracted from the main experiment in Sec. III B). The amplitude variance is indicated by ±1 Standard Error, SE (= SD/$\sqrt{}$N; N = 10). The results of the comparative statistical testing of the amplitude values from the ER-2 and the "Simulated ER-3A" are indicated at each level.

which are shown in Fig. 10. At 20 and 40 dB nHL there are significant differences ($p < 0.01$) between the amplitude distributions obtained by the ER-2 and the Simulated ER-3A, - at 60 dB nHL no significant difference is found. At 20, 40, and 60 dB nHL no significant differences are found between the amplitude distributions for the true and simulated ER-3A ABRs, and the two sets of waveforms look very similar. To ease the comparison, the simulated ER-3A (thick line) and the true (thin line) Grand Average waveforms are placed on top of each other in the middle, horizontal section of Fig. 10.

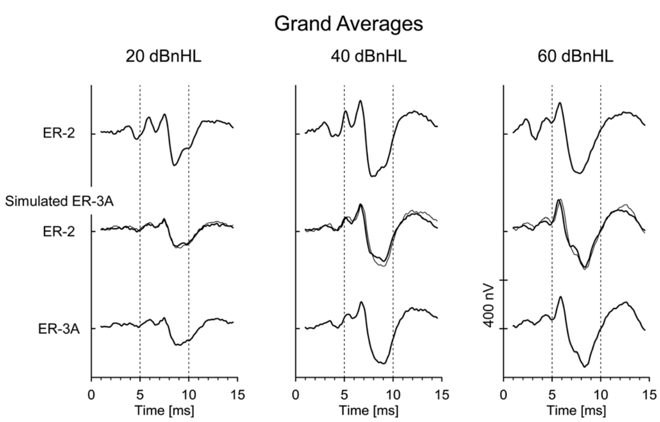

FIG. 10. Grand Average ABR waveforms from N = 10 ears, in response to the LS-Chirp at three stimulus levels [dB nHL]. The three waveforms at the top are the responses to the ER-2; the three in the middle are the responses to the "Simulated ER-3A," and the three at the bottom are the responses to the ER-3A. In the middle, the responses to the ER-3A are re-plotted (thin line) to ease a visual comparison to the "Simulated ER-3A" waveforms. The Grand Averages are obtained by time-shifting the underlying individual waveforms according to the wave-V latency, as described in the text.

C. Discussion

The results from this experiment seems to indicate that it is the ER-2 earphone's amplitude response, providing much more high-frequency energy than the ER-3A, that is responsible for the ABR-differences that are observed between the two earphones when using chirp stimuli. When the simulated LS-Chirp is presented by the ER-2 earphone with an amplitude response similar to the amplitude response of the ER-3A and with a phase response of the ER-2, ABRs are obtained with characteristics comparable to those obtained with the ER-3A.

V. SUMMARY AND CONCLUSION

For standardized calibration, the Ear Mould Simulator, DB 0370 is normally used to connect the insert earphones to the occluded-ear simulator. However, this ear canal extension generates resonances around 4500 Hz and therefore distorts the measured amplitude responses. For a more realistic estimation of *in situ* conditions the ear canal extensions DB 2012 or DB 2015 should be applied.

Significant differences in sensitivity exist between the ER-3A and ER-2 earphones; for the psycho-physical calibration of a 1000 Hz pure tone the difference is 28.5 dB, and for a 100 μs click the difference is 32.0 dB.

The amplitude and the phase responses (or group delay functions) are markedly different between the ER-3A and ER-2 earphones. The ER-3A has an amplitude response like a band-pass filter (from 1400 Hz, 6 dB/octave to 4000 Hz, −36 dB/octave) and a group delay function that exhibits large "ripples" of up to ±0.5 ms. Compared to this, the ER-2 has an amplitude response, a delay-compensated phase response, and a group delay function which all are smooth and flat all the way up to and above 10 000 Hz. Due to distortion in the ER-2 the maximum output of a 100 μs click is in practice restricted to 65 dB nHL.

Significant differences also exist between the two earphones' ability to evoke click and chirp ABRs. At all levels the ER-2 generates slightly larger click-ABRs than the ER-3A, and at lower levels (< 60 dB nHL) the ER-2 generates much larger chirp-ABRs than those generated by the ER-3A. Upward spread of excitation with the chirps appears to kick-in at lower levels for the ER-2 (between 40 and 60 dB nHL) than for the ER-3A (between 60 and 80 dB nHL). Finally the ABRs generated with the ER-2 earphone are in general resolved with more details than those generated with the ER-3A. All these differences seem to be due to the increased high-frequency response of the ER-2 compared to the ER-3A.

The group delay functions of the two earphones show an average group delay of 1 ms, but whereas the group delay function for the ER-2 is relatively flat it is highly rippled for the ER-3A. Theoretically, a rippled group delay function could influence the effect of the delay compensation offered by the chirps. However, no such influence is apparent in the group data evaluated in the present study.

All in all, the results of this study seem to indicate that the ER-2 earphone is a better choice than the ER-3A when using chirp stimuli to record broadband ABRs in normal-hearing adults at stimulus levels below 60 dB nHL.

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[1]Amplitude responses deviate by less than 0.4 dB (ER-2) and 1.5 dB (ER-3A) in the frequency range 200–8000 Hz.

[2]The International standards, IEC 60645-3 (2007) and ISO 389-6 (2007), recommend that the abbreviation, peSPL, is used for the term, peak-to-peak equivalent sound pressure level. However, to avoid the common confusion between peak values and peak-to-peak values, the longer but more correct abbreviation, p.-p.e.SPL, is used throughout this paper.

[3]These RETSPL-values refer to the condition when the two insert earphones are coupled to the occluded-ear simulator (IEC 60318-4, 2010) using the DB 0370 Ear Mould Simulator.

[4]The acoustical delay due to the length of the long tubing and the ear tips is approximately 0.85 ms (ER-2) and 0.81 ms (ER-3A). However, the total delay from the electrical input to the acoustical output in the occluded-ear simulator (IEC 60318-4, 2010) using the DB 2012/15 ear canal extension, is approximately 1 ms for both earphones according to the measured group delay functions shown in Fig. 4.

[5]The group delay function, t_g, of a linear system, is defined as the negative slope of the phase response and describes how much the envelope of an input signal containing a narrow band of frequencies is delayed from the input of the system to the output: $t_g(\omega) = -\frac{d\theta(\omega)}{\omega}$, where $\theta(\omega)$ is the phase response, ω is the radian frequency ($= 2\,\Pi$ f), and f indicates frequency.

[6]This new MAP-estimate is obtained by using the standardized pure-tone RETSPL-values for the ER-3A (ISO 389-2, 1994) and the corresponding values for the ER-2 (Han and Poulsen, 1998). These reference values refer to measurements in the occluded-ear simulator (IEC 60318-4, 2010) using the DB 0370 extension. First, each set of reference values are corrected for the differences between using extension DB 2012/15 and DB 0370 as described in Sec. II and shown in Fig. 2. Next, the final MAP-estimate is obtained by taking the mean of the two sets of corrected reference values.

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